Predicting dynamics of soil organic carbon mineralization with a double exponential model in different forest belts of China

YANG Li-xia[1, 2], PAN Jian-jun[3], YUAN Shao-feng[4]

[1] *Nanjing Institute of geography and Limnology, Chinese Academy of Sciences Nanjing, Nanjing 210008, P. R. China*

[2] *Graduate School of Chinese Academy of Sciences Beijing, Beijing 100039, P. R. China*

[3] *Institute of Resources and Environment of Nanjing Agriculture University, Nanjing 210095, P. R. China*

[4] *Collage of public management of Zhejiang Gongshang University, Hangzhou 310035, P. R. China*

Abstract: The dynamics of soil organic carbon (SOC) was analyzed by using laboratory incubation and double exponential model that mineralizable SOC was separated into active carbon pools and slow carbon pools in forest soils derived from Changbai and Qilian Mountain areas. By analyzing and fitting the CO_2 evolved rates with SOC mineralization, the results showed that active carbon pools accounted for 1.0% to 8.5% of SOC with an average of mean resistant times (MRTs) for 24 days, and slow carbon pools accounted for 91% to 99% of SOC with an average of MRTs for 179 years. The sizes and MRTs of slow carbon pools showed that SOC in Qilian Mountain sites was more difficult to decompose than that in Changbai Mountain sites. By analyzing the effects of temperature, soil clay content and elevation on SOC mineralization, results indicated that mineralization of SOC was directly related to temperature and that content of accumulated SOC and size of slow carbon pools from Changbai Mountain and Qilian Mountain sites increased linearly with increasing clay content, respectively, which showed temperature and clay content could make greater effect on mineralization of SOC.

Keywords: Soil organic carbon; Organic carbon mineralization; Double exponential model; Active carbon pools; Slow carbon pools; Mean resistant times (MRTs)

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Introduction

The dynamics of soil organic carbon (SOC) play an important role in global C cycle. It is estimated that soil organic carbon contains 1580 Gt of C as compared to 610 Gt C in terrestrial vegetation and 750-Gt C in the atmosphere (Schimel 1995). Approximately 70% of the global soil C inventory resides in forest ecosystems (Hudson *et al*. 1994). A relatively little change in forest soil C inventories could have important implication for the global C budget. It is important for us to understand how the dynamics of forest SOC may affect both atmospheric CO_2 concentrations and soil quality following large-scale changes in climate or land use (Garten *et al*. 1999).

SOC dynamics are complex, involving a wide array of organic constituents (Sollins *et al*. 1999) with mean resistant times (MRTs) that range over different orders of magnitude (Goh *et al*. 1984; Paul *et al*. 2001a). To describe exactly SOC mineralization and turnover rate, SOC pools are divided into two pools, active carbon pools and slow carbon pools according to turnover time. The active carbon pools are the most rapidly mineralized by the soil microorganism. The slow carbon pools are the most slowly mineralized.

At present, the combination of long-term laboratory incubation of soil with measurements of the CO_2 evolved and models have been widely used to differentiate different carbon pools in soil.

By analyzing the CO_2 release rates, a variety of mathematical models can be fitted to derive estimates for functional carbon pool sizes and their turnover rates. Both complex mechanistic and simple kinetic models have been used for this purpose (De Willigen. 1991). The mechanistic models are complex, process-based and require more data input in the field. The kinetic models mainly rely on laboratory incubations to obtain parameters and account for basic carbon turnover process. At present, the double exponential models have frequently been used to distinguish active carbon pools and slow carbon pools (Deans *et al.* 1986; Gregorich *et al.* 1989; Cabrera 1993). The separate determination of active carbon pools and slow carbon pools is important for estimating the dynamics of SOC.

The objectives of this study are (i) to describe SOC mineralization by a series of long-term laboratory incubation data of forest soils with constant temperature (25 °C) and water-holding capacity (60% WHC) and known histories of management and different vegetation types; (ii) to determine SOC pool sizes and turnover rates according to the double exponential models; (iii) to examine the effects of temperature, clay content and elevation on SOC mineralization rates in two characteristic forest areas including Changbai Mountain (CBM) and Qilian Mountain (QLM).

Materials and methods

Soils and properties

Seven soil profiles were collected from two characteristic forest areas including different sites of Changbai Mountain and Qilian Mountain (Table 1, 2).

Changbai Mountain (CBM) area is located in Jilin Province, northeast China (127°38′–128°10′E, 41°42′–42°10′N), including Antu, Wusong and Changbai Counties, covering total area of 167 081 km^2. Changbai Mountain belongs to coniferous and

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Biography: YANG Li-xia (1976-), female, Ph.D. Candidate in Nanjing Institute of geography and Limnology, Chinese Academy of Sciences Nanjing, Nanjing 210008, P. R. China (E-mail: yanglixianj2001@163.com or yanglixia_39@hotmail.com)

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broadleaf mixed forest bioclimatic zone and continental Temperate Zone, where the annual precipitation is 700–1400 mm, the mean annual temperature is 5 °C, minimum temperature is less than -40 °C, and the rain period is 209 days. The dominant soils in the area are brown coniferous forest soils, dark-brown soils, volcanic ash soils and bog soils. Elevation is 7 202 –600 m, and 4-types zones of dominant vegetation are distributed respectively with elevation increase, there are coniferous and broadleaf mixed forest bioclimatic zone (720–1 100 m), dark coniferous forest bioclimatic zone (1 100–1 700 m), Asian birch forest bioclimatic zone (1 700—2 000 m) and tundra bioclimatic zone (>2 000 m).

Qilian Mountain area is located in Gansu Province, northwest China (99°20′–99°50′E, 38°30′–38°55′N). The climate belongs to semiarid climate. The mean annual air temperature is -0.3 °C, the annual rainfall is 440 mm, and duration of frost-free period is 90-120 days. Vegetation distribution vertically with the variation of climate and terrain, and can be divided into three zones: Mountainous prairietimber zone, subalpine brush and partum zone, and subalpine nival sparse vegetation zone.

Table 1. Location and elevation of samples sites from Changbai and Qilian Mountain sites *

Sample	CBM1	CBM2	CBM30	QLM1	QLM2	QLM4	QLM11
Longitude	128°04′07″	128°04′32″	128°06′32″	99°21′36″	99°24′31″	99°38′03″	99°28′55″
Latitude	42°02′25″	42°03′41″	42°25′37″	38°47′21″	38°45′28″	38°45′13″	38°37′47″
Elevation(m)	2261	1923	706	3004	2923	2668	3890

Notes: * CBM represents different Changbai Mountain samples sites; QLM represents different Qilian Mountain samples sites.

Table 2. Properties of soil profiles in different Changbai and Qilian Mountain sites

Sample sites	Depth (cm)	Organic carbon (g•kg^{-1})	pH	Clay (%)	Soil type	Vegetation
CBM1	0-11	65.02	5.04	9.39	Volcanic ash	Niupi ericaceous
	11-17	12.31	5.52	4.84		
CBM2	0-19	61.46	5.24	15.13	Humic volcanic ash	Chinese yue birch
	19-36	26.81	5.59	19.54		
CBM30	0-11	34.93	5.81	6.82	Dark-brown	Mei ren pine
	11-20	5.82	5.97	2.71		
QLM1	0-30	65.78	8.04	13.72	Subalpine grass	Grass
	30-60	62.25	8.41	14.83		
QLM2	0-30	89.03	8.11	13.70	Upland Chestnut	Qinghai spruce
	30-60	71.65	8.35	13.82		
QLM4	0-30	80.82	8.16	14.93	Upland Chestnut	Fir
	30-60	70.63	8.17	13.12		
QLM11	0-30	60.51	8.15	14.82	Alpine meadow	Meadow and shrubs
	30-60	45.16	8.19	14.63		

Sampling and laboratory incubation

In sample sites, seven soil samples were collected according to soil types and vegetations in December, 2001 and July, 2003. Six cores were mixed from each field replicate (three replicates) by using a soil probe. Soil cores were collected according to soil genetic horizons. Moist soil samples were air-dried and sieved to pass a 2-mm sieve. Recognizable plant fragments were removed by hand picking. Total C was measured by wet oxidation (Nelson *et al.* 1975)

The 100-g soil samples of each field replicate were incubated in 250-mL glass jars in the dark at 25°C with 60% water holding capacity for 90 days. The jars were normally closed but opened periodically to maintain an aerobic condition for the soils. Water loss in the jars was replenished every time when the jars were opened. No leaching was conducted during the course of incubation. The evolved CO_2 was trapped in 25 mL of 0.4 N NaOH. Controlled jars had no soil. Evolved CO_2 was precipitated by the addition of $BaCl_2$ and measured by titration of residual NaOH to pH 7.0 with 0.4 N HCL. The evolved CO_2 was measured daily during the first week and every 3–4 days in the following 2 weeks gradually to the end of the incubation period. Pool sizes and MRTs for organic C pools were determined by analyzing CO_2 kinetics (Fig. 1).

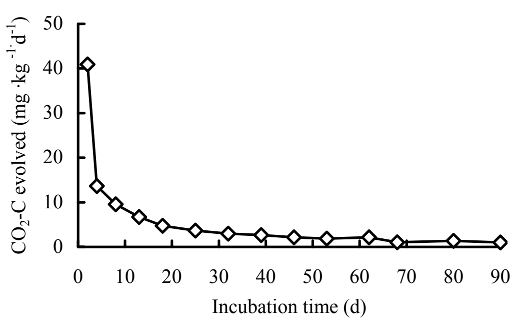

Fig. 1 Rate of CO_2 evolution during laboratory incubation in the Changbai Mountain 1 (0-11) site.

Model description

SOC pools are divided into active carbon pools and slow carbon pools according to their turnover time by using the double exponential model. The two exponential models can be presented as:

$$C_t = C_a e^{-k_a t} + C_s e^{-k_s t} \quad (1)$$

where, C_t is total organic carbon at time *t*; C_a and C_s are the sizes of the active and slow carbon pools; k_a and k_s are rate constants for active and slow carbon pools. *t* represents incubation days.

Model fitting and statistical analysis

Equation (1) was fitted with the non-linear regression (SPSS 10.5) that was used in the Marquardt algorithm and an iterative process to find the parameter values that could minimize the residual sum of squares. The resultant pool sizes and their mineralization rate constants could be sensitive to the initially assigned parameter values and the iterative steps size. Generally, the automatically estimated initial parameters resulted in acceptable parameter values. In some cases, initial parameter values and the iterative steps size must be adjusted by handwork till to obtain sensible results in reasonable ranges, for example, rate constants could not be negative; the sum of active and slow carbon pools should not exceed total SOC.

The standard deviation of the parameters, the residual mean square (RMS) and the *F*-values of the curve fitting were calculated. The model which gave a randomized distribution of the residuals together with the lowest value of RMS and high *F*-value was chosen as the best fit (Little *et al*. 1975).

Results and discussion

Dynamics of SOC mineralization and pools

The dynamics of SOC mineralization followed a two-phase pattern that SOC was rapidly decomposed at the early incubation stages and its decomposition gradually slowed down in a comparative steady stage. This reason was that SOC was composed of two parts: easily mineralizable and anti-mineralizable components. The former could fast decompose at the early incubation stages. The later slowly decomposed. Although the trends of SOC mineralization were similar, there were differences between SOC pools in different samples.

SOC decreased from surface to subsurface horizons. There were similar distributions of active carbon pools. The active carbon pools were comprised of 2.5% to 8.5% of SOC in surface soils, approximately 1% to 2% in subsurface horizons with an average of MRTs for 24 days excluding 6.36% in the sample site of CBM30 (11-20). However, the slow carbon pools increased from surface to subsurface horizons and varied from 91% to 97% of SOC in surface soils with an average of MRTs for 79 years, approximately 94% to 99% in subsurface horizons with an average of MRTs for 179 years (Table 3).

The proportion of active carbon pools in Changbai Mountain sites was greater than that in Qilian Mountain and Changbai Mountain had the lowest MRTs for both the active and slow carbon pools. Pool size of slow carbon pools in Qilian Mountain sites was greater and MRTs of slow carbon pools was longer than that in Changbai Mountain sites. This indicted that forest soils in Qilian Mountain sites were more difficult to decompose. From Figure 2, the initial total SOC contents were not related to active carbon pools. However, there was a close correlation between the initial total SOC contents and slow carbon pools (R^2=0.9955). In conclusion, these results showed forest soils from both Changbai Mountain and Qilian Mountain sites were in comparative steady and protected state.

Table 3. Pool sizes and C-mineralization kinetics of soil for the active and slow carbon pools from Changbai and Qilian Mountains sites

Sample sites	Depth (cm)	Total organic carbon (g•kg^{-1})	Active carbon pools			Slow carbon pools		
			Ca (g• kg^{-1})	Ca/SOC (%)	MRT (d)	Cs (g•kg^{-1})	Cs/SOC (%)	MRT (yr.)
CBS1	0-11	65.02	2.05	3.15	18	62.97	96.86	57
	11-17	12.31	0.13	1.06	12	12.18	98.94	381
CBS2	0-19	61.46	2.79	4.54	30	58.67	95.46	74
	19-36	26.81	0.73	2.72	44	26.08	97.28	183
CBS30	0-11	34.93	2.87	8.22	14	32.06	91.78	52
	11-20	5.82	0.37	6.36	8	5.45	93.64	46
QLM1	0-30	65.78	3.1	4.71	17	62.68	95.29	54
	30-60	62.25	0.76	1.22	16	61.49	98.78	211
QLM2	0-30	89.03	4.56	5.18	38	84.47	94.88	98
	30-60	71.65	1.67	2.33	21	69.98	97.67	114
QLM4	0-30	51.78	2.04	3.94	18	49.74	96.06	83
	30-60	70.63	1.02	1.44	29	69.61	98.56	171
QLM11	0-30	60.51	1.82	3.01	32	58.69	96.99	137
	30-60	45.16	0.83	1.84	19	44.33	98.16	274

Notes: All regression coefficients significant at *P*<0.001. Ca---- Active carbon pools; Cs---- Slow carbon pools; SOC---- Soil organic carbon.

Effect factors on SOC mineralization

SOC pools were different among different forests. The proportion of active carbon pools followed the order of CBM>QLM. However the MRTs of slow carbon pools had inverse trend. The differences showed that SOC mineralization was affected by environment and other factors.

Effects of Temperature

Dynamics of SOC mineralization are strongly affected by temperature because soil microbial processes are a function of temperature (Insam1990; Kirschbaum 1995; Winkler *et al.* 1996). So temperature was an important factor controlling both the amount and turnover time of SOC mineralization. While a significant correlation between temperature and SOC mineralization

is well established (Singh *et al.* 1977; Raich *et al.* 1992; Lloyd *et al.* 1994; Kirschbaum1995; KaÈ tterer *et al.* 1998), there is no uniform function to describe the relationship. Some authors qualitatively described the effect of temperature: at higher temperatures, the easily decomposable fraction was mineralized more quickly than at lower temperatures. This implies that after a certain time there will be more easily decomposable matter left over in the low-temperature treatment than in the high-temperature one. Because the mean annual temperature in Changbai Mountain was higher than in Qilian Mountain, SOC in Changbai Mountain mineralized faster than in Qilian Mountain. SOC mineralized was mostly composed of accumulations of active carbon pools. So the proportion of active carbon pools followed the order for CBM>QLM.

Effects of soil texture

SOC is well protected by fine particles (Sorenhen 1981; Hassink 1994b). It was apparent that the fine texture of clay soil reduced the amount of SOC mineralization which contributed to accumulation of SOC. Clay content affected the turnover of active carbon pools and the stabilization efficiency of slow carbon pools. The mean resistant times (MRTs) of active carbon pools from Changbai Mountain sites increased linearly with increasing clay soil content (R^2 =0.9726), however it was not obvious in the Qilian Mountain sites (Figure 3). The reason might be that the clay contents of soil samples in Qilian Mountain sites ranged between 13.12%–14.93% and had not significantly differentance. Data analysis showed that content of accumulated SOC and size of slow carbon pools from Changbai Mountain and Qilian Mountain sites increased linearly with increasing clay content, and R^2 was 0.7033 and 0.6575, respectively (Fig. 4). In laboratory studies, control temperature, moisture, and soil with fine texture (more clay content) could reduced SOC mineralization and contributed less CO_2 to the atmosphere. Our results were conformed to other conclusions that soil organic matter (SOM) increases linearly with clay content at regional and global scales (Parton *et al.* 1993; Schimel *et al.* 1994), but some authors thought that the effect of clay content on soil C mineralization was weak (Motavalli *et al.* 1994) or nonexistent (Sørenson 1981; Hassink *et al.* 1993; Scott *et al.* 1996). These divergences should be studied further through lots of data.

Effects of elevation

Mean annual air and soil temperatures declined along the elevation gradient by approximately 0.5 °C with every 100-m increase in elevation. It is considered that air and soil temperatures decrease with elevation and litter decomposition rate also decreases according increasing elevation (Garten *et al.* 1999). It is feasible to use elevation gradients as an approach for testing the effect of environmental variables on the dynamics of forest SOC. From Figure 5, accumulated SOC content increased linearly with the increasing elevation. There was a similar trend in the slow carbon pools. This showed that SOC was steadier in high elevation. The result is consistent to Garten's conclusion (Garten *et al.* 1999). However, the relationship between elevation and the SOC mineralization rate did not show a clear negative correlation mainly because elevation gradients were often accompanied by natural changes in climate (both MAT and moisture), vegetation type, soil properties (chemistry, texture, and parent material), and soil nutrient availability.

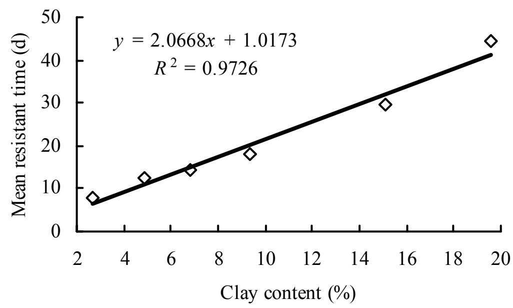

Fig. 2 Relationships between total organic C and both active and slow carbon pools in Changbai and Qilian Mountain sites

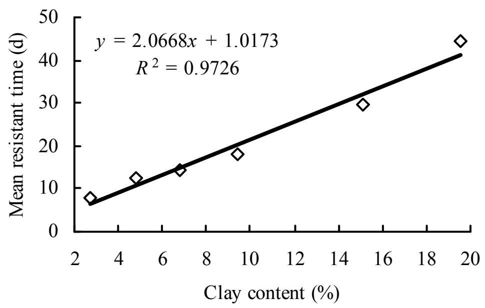

Fig. 3 Relationships between soil clay content and mean resistant time of the active carbon pools from Changbai Mountain sites

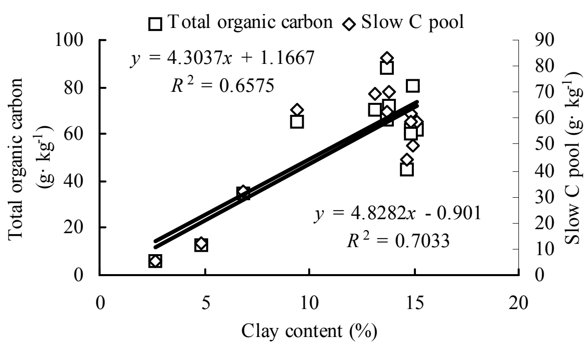

Fig. 4 Relationships between clay content and both total organic carbon and slow carbon pools from Changbai and Qilian Mountain sites

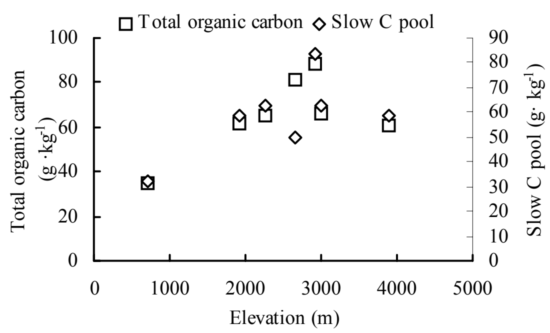

Fig. 5 Effect of elevation on total organic carbon and slow carbon pools from Changbai and Qilian Mountain sites

Conclusions

The dynamics of SOC mineralization followed a two-phase pattern that SOC was rapidly decomposed at the early incubation stages and its decomposition gradually slowed down in a comparative steady stage. This reason was that SOC was composed of two parts: active (easily mineralizable) and slow carbon pools (anti-mineralizable components). This could be described by the two exponential models. Many researches have shown that the two exponential models could availably be interpreted as dynamics of forest SOC (Deans *et al.* 1986; Gregorich *et al.* 1989; Cabrera 1993). Pool sizes and MRTs of the active and slow carbon pool were determined by the models. The active carbon pools were comprised of 1% to 8.5% of SOC in soils with an average of MRTs for 24 days. The slow carbon pools varied from 91% to 99% of SOC in soils with an average of MRTs for 179 years, which reflected the degrees of stabilization of C. These data showed soils from Changbai Mountain and Qilian Mountain sites contributed less CO_2 to atmosphere. The analyses of pool sizes and MRTs give accurate estimates of SOC dynamics for decision making in global change calculations.

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